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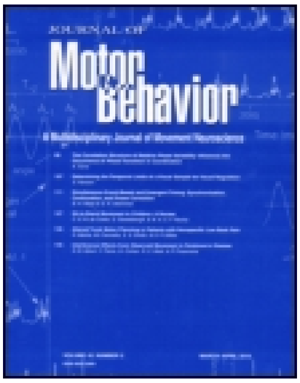

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Geometries and Dynamics of a Rod Determine How It Is Used for Reaching

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Geometrics and Dynamics of a Rod Determine How It Is Used for Reaching

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ABSTRACT. Displacing an object with a hand-held rod provided a simple paradigm for studying tool use. The authors asked how reaching was affected by manipulations of rod properties. Adults held a rod (length = .10 to 1.5 m), with its tip in the air; walked toward an object on a table; chose a place to stop; and displaced the object with the rod's tip. In 3 experiments (*N*s = 9, 22, and 17 participants), the authors manipulated rod length, mass, and mass distribution to determine whether and how geometric and dynamic properties affected the chosen distance and the posture. Both the chosen stopping distance and the postures were well accommodated to rod characteristics. Postural adaptations took place only in the arm, which was organized as a synergy. Predictably, rod length explained most of the variance, but small and reliable differences in both distance and posture depended on mass and mass distribution. The chosen distance anticipated not only rod length but also the upcoming posture needed to control the rod.

Key words: affordance, dynamics, postural control, reaching, tool use

The amount of routine tool use in human behavior stands in sharp contrast to the amount of attention that issue has received in psychological studies. In the few studies addressing tool use, the authors appear to agree on the definition of tools as objects that can be attached to the body to adjust the capacity for action. The changes in the capacity for action when using a tool tend not to be the concern in those studies, however. Perceived action capacity was the focus in the present research; we asked which aspects of an action are affected by particular properties of tools. We phrased that question in the context of a simple task involving a tool: displacing an object with a hand-held rod.

Traditionally, the focus in studies of tool use has been on cognitive abilities needed to solve a problem (Bates, Carlson-Luden, & Bretherton, 1980; Köhler, 1925; McCarty, Clifton, & Collard, 1999; cf. Steenbergen, Van der Kamp, Smitsman, & Carson, 1997, and Van Leeuwen, Smitsman, & Van Leeuwen, 1994). The emphasis in such studies was on determining whether children, in particular, understand the potential means to an end that an object might be said to offer. The concern in most of that work was the features on the basis of which a child selects an object to perform a certain task. Tool use was studied as a means of uncovering cognitive mechanisms, particularly how an individual conceives of an object's features when using it as a tool.

In the present study, we approached tool use as an action problem instead of as a cognitive problem, because we believe that there lie its origins (cf. Smitsman, 1997). Tools are used in situations in which our own action system falls short or when the action goals can be achieved more conveniently. Hence, individuals use tools to expand and enhance possibilities for action. After Gibson (1979), we label the environmental properties that afford opportunities for action *affordances*. Their counterparts in the organism, that is, the possible ways the action system can be organized into functional units, are called *effectivities* (Shaw & Turvey, 1981; Turvey & Shaw, 1979). Affordances and effectivities are mutual concepts, and the realization of an action reflects the fit between them (cf. Shaw, Flascher, & Kadar, 1995, and Warren, 1984). The characteristics of actions reveal properties of the fit.

Properties of the action system such as segment length, segment mass, and muscle strength determine, in part, the way the action system can be organized into functional units so that it can perform a certain task. Organization in functional units makes it possible for the end-effector of the action system to be properly oriented and to be directed with the right force relative to the environment, given a specific task. If action system properties, such as length or

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mass, change—as is the case with tool use—then the action system might have to be organized differently so that it can maintain the relation between end-effector and environment. We were interested in two main changes in the action system, which are entailed by using a tool: (a) With most tools, the point where effective contact is made with the environment is displaced from the body to the tool (i.e., the end-effector is displaced), and (b) the dynamics of the effector system (e.g., the forces and torques in the joints and muscles) changes. In short, using a tool changes the geometrics and the dynamics of the action system.

In that context, we define expert tool use: The implement and the action system function as an integrated whole; the new action system consists of body plus tool (body + tool). That means that the affordances in the environment are in reference to the body + tool system. Because the means by which an affordance might be seized are called effectivities, body + tool can be understood as a change in the effectivity (cf. Shaw et al., 1995; Smitsman, 1997). Couched in those terms, our focus was on how changes in effectivities and, thus, changes in affordances manifest themselves in action. Note that affordances should prospectively affect the actions: Changes in properties of the body + tool system require anticipatory adjustments reflecting the new action system.

In the present study, giving an individual a rod changed his or her effectivity for displacing an object. More particularly, participants were asked to walk toward a table while pointing a rod upward and to select the distance from which they could most comfortably displace a small cylinder on a table. They then lowered the rod and slid the cylinder back and forth with the tip of the rod. Presumably, one's ability to displace the cylinder depends not only on the length of the rod but also on one's ability to manipulate the rod with muscular forces and to balance the body, given the rod's kinetic properties (e.g., mass, mass distribution). Still, a comfortable reach can be performed in many ways; there are a large number of degrees of freedom available in the reaching system. In our experimental setup, the degrees of freedom included the place to stop and the posture that unfolded to displace the object. By the time the object on the table is displaced, all the degrees of freedom in the body have been constrained. Performing a comfortable reach requires that the selected distance to the table both accommodates the length of the rod and allows for a comfortable posture. That constraint implies that postural adaptations necessary to control the rod should be reflected in the adopted reaching distance. The empirical question we tried to answer in the present study was the following: What characteristics of the rod constrain particular aspects of the action system, in particular, the selected distance to the table and the posture?

Dean, Brüwer, and their colleagues investigated adaptations of posture to changes in length of a hand-held pointer. In a series of experiments (Cruse, Brüwer, & Dean, 1993; Cruse, Wischmeyer, Brüwer, Brockfeld, & Dress, 1990; Dean & Brüwer, 1994, 1997), participants were asked to make pointing movements, with and without pointers, in a two-dimensional plane at approximately shoulder height. In some experiments, the pointer varied in length. The tip of the hand or pointer had to successively touch two points, and an obstacle placed between those points had to be avoided. Joint angles and kinematics of the trajectories depended on the size of the obstacle and the length of the pointer. Dean and Brüwer (1997) suggested that dynamic factors related to arm posture, for instance, were of importance for the observed behavior. Those findings led us to expect that in our task, the use of a rod would affect postural degrees of freedom. We shared interest with Dean and Brüwer in the postural organization underlying the reach with an extension. However, we were also interested in whether changes in the postural organization are anticipated in the chosen distance to an object. Moreover, we did not limit our focus to the elbow angle and the shoulder angle but included the trunk and other body segments that might be relevant to making a comfortable displacement.

We began our experiments by trying to establish the phenomenon, that is, to establish the degree of participants' sensitivity to characteristics of rods. In Experiment 1, participants used light wooden rods to make a reach. In subsequent experiments, we changed geometric and dynamic properties of the rods to expose underlying variables and mechanisms; we varied length and mass in Experiment 2, and length, mass, and mass distribution in Experiment 3.

EXPERIMENT 1

Given the ease and speed with which people organize their action systems to the properties of everyday utensils, we expected that participants would immediately adapt their actions when using a rod for reaching. To determine participants' degree of sensitivity to changes in rod length when making a reach, we changed the reaching system in a very simple way: Participants used lightweight wooden rods of different lengths to displace an object. We studied whether and how the selected distance to the object and posture were adapted.

To assess which postural adaptations were to be expected when participants reach with a rod, we started by examining the postural organizations participants used to perform a goal-directed reach without a rod. We assumed that posture is organized to meet two fundamental goals: (a) the maintenance of stability and (b) arm movement toward and displacement of the goal. One can achieve postural stabilization by coordinating the leg, hip, and trunk joint motions (e.g., Crenna, Frigo, Massion, & Pedotti, 1987; Oddsson, 1988; Patton, Pai, & Lee, 1999). The actual reaching movement in a two-dimensional plane is performed with a close linkage between motion at the elbow and at the shoulder (e.g., Lacquaniti & Soechting, 1982). The results of studies whose focus was on the relation between trunk and arm during reaching and grasping—participants were seated and reached to targets within and beyond reach—have indicated that the trunk serves as a postural stabilizer (Kaminiski, Bock, & Gentile, 1995; Ma & Feldman, 1995; Saling, Stelmach, Mescheriakov, & Berger, 1996; Wang & Stelmach, 1998). Ma and Feldman have suggested that posture is organized into two synergies during reaching: (a) The first is that the relation between trunk and arm is controlled, leaving the hand unchanged. (b) The other synergy concerns the control of the arm to bring the hand to the target. One of the key issues we raise in this article is whether similar postural synergies are used when a reach has to be made with a rod.

How did we expect the rod to affect the postural synergies? We reasoned that a long rod requires more control than a short rod because movements of the wrist will result in larger deviations at the tip of a long rod than at the tip of a short rod. That statement implies that longer rods demand a posture that provides for more stable control of the rod. The focus in some of our analyses, therefore, is on stability-related postural synergies adopted to control rods of different lengths. Moreover, rod length will affect the kinetics in the arm and, thus, the arm posture. Note that the horizontal foot-to-hand distance created by postural synergies should be reflected, prospectively, in the stopping place. That expectation led us to ask whether the following trio of characteristics—the length of the rod, the posture of the arm, and the stability-driven choice of body posture—is reflected in the selected distance to the table.

Method

Participants

The 9 participants ranged in age from 20 to 38 years; 7 were women, and 2 were men. All were right-handed and either volunteered to participate in partial fulfillment of a course requirement or were paid a fee for their participation.

Materials

A 50-g PVC cylinder (diameter 5 cm, height 6 cm) was placed on a tabletop (25 × 25 cm). The height of the table was adjusted to the participant's wrist height with the arm at the side. The back of the cylinder was placed against a barrier 12.5 cm high, and the front of the cylinder was aligned with the front edge of the table; that placement ensured that participants used the tip of the rod to displace the cylinder.

The rods had a diameter of 1.25 cm and ranged in length from 0.1 to 1.5 m, in 0.1-m steps. The rods were constructed from wood (density 0.67 g/cm^3). A handle was added to each rod, extending it 11.5 cm. A small plastic disc divided the handle from the rod.

Design

There were 16 conditions, formed by 15 lengths and the tip of the fingers (which appears in our tables and figures as a rod length of 0.0). Each condition was presented 10 times in randomized blocks, for a total of 160 trials per participant, run in one session.

Procedure

The rods stood in a rack on the floor, about 3 m from the to-be-moved target. The participant grasped the rod designated by the experimenter and rotated the rod so that the tip would point upward. Note that in the process of rotating the rod, participants could explore properties of the rod related to its torque and resistance to rotational acceleration (i.e., variables that became important and were tested in later parts of the study). Participants walked toward the table while holding the rod at an angle of about 45° upward from the horizontal (Figure 1). The task was to stop at a place from which the cylinder could be displaced most comfortably; then, the object was displaced approximately 15 cm back and forth with the tip of a rod (or with the tip of the fingers, in the control condition). Note that the rod was visible at all phases of the task's execution. The approach, reach, and displacement were videotaped. We used a video-digitizing system to determine the positions of the handle of the rod, the tip of the rod, and anatomical landmarks (toe, ankle, knee, hip, shoulder, elbow, and wrist) in a two-dimensional (2D) plane at the moment the displacement of the object started. Measurement of the behavior at one moment in the action provided a snapshot view of the behavior. It is obvious that our interest in the dynamics of the body + rod system did not concern the process of unfolding of the reach but whether dynamic aspects of the system affected the reaching distance in an anticipatory way and how the posture with which the object was displaced changed according to the dynamics.

We measured reaching distance as the distance between the table and the foot nearer to the table. On most trials, the feet were closely aligned, but we always measured reaching distance from the foot closest to the table. Postural angles were computed from the positions of the joints. The hip angle was the measure of the bending of the trunk; the positions of the knee, hip, and shoulder were used in that measurement. At 0°, the trunk was in line with the thigh. Forward bending (shoulder in front of the hip) had a positive value, whereas backward bending in the hip gave a negative value. At a shoulder angle of 0°, the arm aimed along the trunk. Negative angles indicated that the upper arm was behind the shoulder, also referred to as retroflexion, and positive angles indicated anteflexion, that is, the upper arm was anterior to the shoulder. A fully extended elbow angle was defined as 180°, and smaller angles denoted flexion.

At the end of an experimental session, we measured participants' body mass, body height, and upper and lower arm lengths.

Data Analysis

We performed a preliminary analysis to remove the outliers from the data. Separate regression analyses on individual participants were performed for the vertical and anterior–posterior values of each joint, with rod length as the independent variable (if mass was also a condition, those analyses were done for each mass condition separately).

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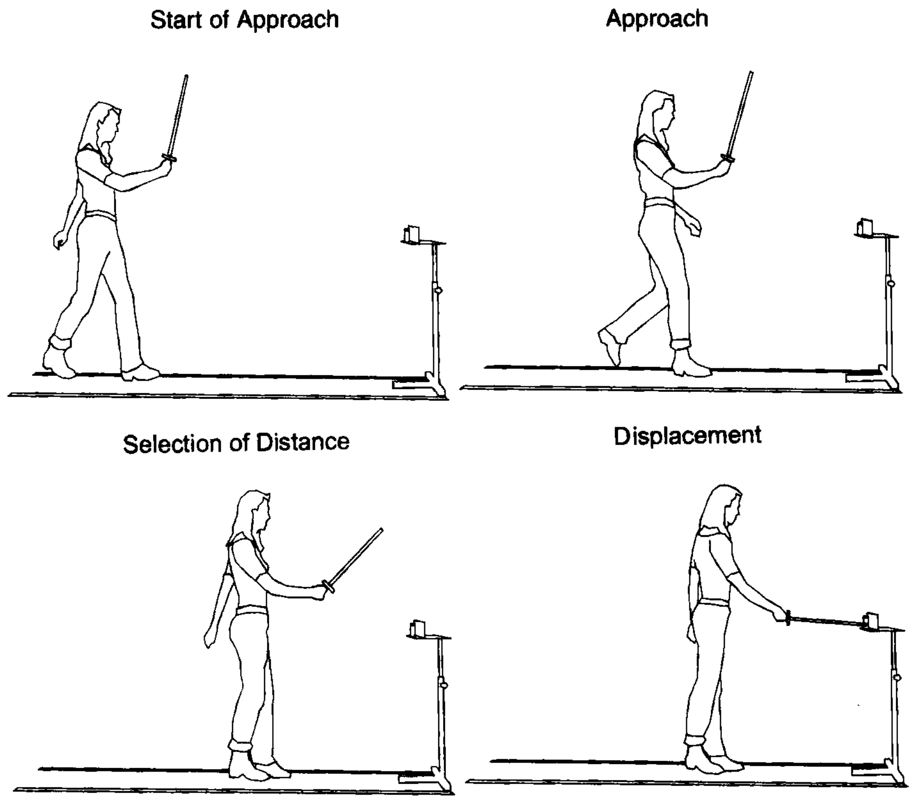

FIGURE 1. Different phases in the unfolding of a trial are shown. Notice that the rod is held up during the approach to the table and that overshoot of the target is prevented.

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Trials on which any nonstandardized residual exceeded four times the standard deviation (*SD*) from the mean of the residuals for that condition were omitted. Of the total of 1,440 trials, 59 were omitted because a residual of the regression analyses exceeded the threshold.

Results and Discussion

Casual perusals of the videotapes showed that participants looked more at the rod's tip in the beginning of the approach phase, whereas in the last part of the approach phase, participants looked more at the to-be-displaced object. Usually, just before lowering the rod, participants looked back and forth from the rod tip to the object.

Reaching Distance

To examine whether the selected distance to the table depended on rod length, we performed a multivariate analysis of variance (ANOVA) on the reaching distance (i.e., the distance of the front foot to the table), with rod length (0, 0.1, . . . , 1.5 m) as a within-participant variable. The analysis was performed on the means of each participant in each condition. We expected that with longer rods, the distance would gradually increase; therefore, we looked only at the linear contrast. Participants chose to stop farther from the table when they used longer rods, $F(1, 8) = 1{,}419.21$, $p < .001$ (see Table 1 for the means and the *SD*s). That analysis showed that reaching distance gradually varied with rod length, implying that participants were highly sensitive to changes in length when making a reach.

To examine whether participants differed in their strategies, we also performed linear regression analyses on the raw data of each participant separately. Those analyses showed that within participants, the reaching distance could be predicted well from the rod length. As can be seen in Table 2, the r^2s were high and the slopes ranged between 0.74 and 0.93. Those results show that rod length explained the vast majority of the variance in the reaching distance within participants. The adaptation in the reaching distance to rod length seemed to be immediate. Participants received visual and haptic feedback through making the displacement; hence, if the distance to the object were systematically uncomfortable (e.g., standing too close with longer rods), a shift in reaching distance over the repeated trials would be expected. However, our data showed no differences over the repeated trials; the data were highly consistent.

Posture

How were adaptations in reaching distance related to adaptations in posture? Preliminary examination of the videotapes

TABLE 1
Means and Standard Deviations for the Significant Effects of the Analyses of Variance in Experiment 1

Rod length (m)	Reaching distance (m) *M*	*SD*	Ankle angle (deg) *M*	*SD*	Shoulder angle (deg) *M*	*SD*	Elbow angle (deg) *M*	*SD*
0.1	0.47	0.12	98.14	4.26	31.31	11.35	150.29	8.66
0.2	0.53	0.17	97.85	4.10	29.13	11.76	148.30	8.19
0.3	0.59	0.15	96.97	3.43	24.41	10.09	145.14	9.18
0.4	0.70	0.10	96.63	3.05	23.30	10.76	142.26	8.49
0.5	0.78	0.10	96.53	3.22	20.81	10.78	139.40	9.55
0.6	0.86	0.10	96.15	3.25	18.18	12.41	136.04	9.35
0.7	0.95	0.08	95.93	3.19	15.71	9.90	135.19	9.27
0.8	1.03	0.11	95.72	3.04	14.96	13.48	134.46	9.75
0.9	1.13	0.10	95.53	3.00	13.58	12.89	132.28	9.37
1.0	1.18	0.11	94.73	2.95	7.82	15.73	128.63	10.40
1.1	1.27	0.10	94.47	3.06	7.24	13.29	127.61	10.27
1.2	1.40	0.12	94.76	3.68	11.29	16.53	129.55	10.91
1.3	1.48	0.10	95.00	3.80	9.04	15.05	128.09	10.54
1.4	1.55	0.13	94.54	2.89	7.76	18.21	128.29	11.93
1.5	1.65	0.12	94.44	3.18	8.31	16.89	127.52	11.49

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TABLE 2
Regression Analyses Between Rod Length and Reaching Distance in Experiment 1

Participant	Intercept	Slope	*F*	*df*	r^2
1	0.35	0.91	3,628.91	1, 151	.96
2	0.44	0.79	2,744.90	1, 148	.95
3	0.41	0.76	4,146.29	1, 150	.97
4	0.43	0.88	3,660.44	1, 153	.96
5	0.31	0.81	3,915.82	1, 153	.96
6	0.40	0.86	3,161.86	1, 155	.95
7	0.54	0.74	1,672.08	1, 150	.92
8	0.29	0.83	1,006.66	1, 149	.87
9	0.23	0.93	6,541.98	1, 154	.98

Note. $p < .001$ for all of the regression equations.

showed that, with shorter rods, participants generally leaned forward somewhat and extended their arms. Some of the participants also rotated the trunk around the vertical axis, but, because of the 2D recording system, that behavior could not be reliably distinguished. With longer rod lengths, the posture was more upright and the elbow was held closer to the body. In Figure 2, we show an example of how 1 participant adapted the posture and distance to different rod lengths. The points shown in Figure 2 are averages over the 10 repeated measures for each rod for Participant 3.

Before we further examine how postural angles changed with rod length, we address whether functional synergies were formed. In particular, we asked whether two synergies were formed: one synergy coordinating the motion between trunk and arm, and one coordinating the motions around the joints of the arm (cf. Ma & Feldman, 1995). To assess synergies, we began by performing regression analyses between the angles.[1] Because participants might have differed, those analyses were done separately for each participant. To examine the arm synergy, we regressed shoulder angle against elbow angle. One can see in Table 3 that for most participants, the adjustments in shoulder and elbow angle had a relatively high correspondence, which suggested to us that the shoulder and elbow angle were organized as a synergy. Remember that the shoulder angle increases when the upper arm is put more forward and the elbow angle increases when the arm is stretched more. The positive slope of the regression lines indicated that the upper arm was put more forward when the elbow was more stretched.

To evaluate whether the adjustments in the hip angle were related to the adaptations in the putative arm synergy, we performed regression analyses with hip angle as the dependent variable and shoulder angle and elbow angle as independent variables. The results for individual participants are presented in Table 4. Two groups of participants could be distinguished on the basis of the explained variance: Four participants had a small r^2 (smaller than 25%), indicating that for those participants, the adjustments in the hip were not coupled to the adaptations in the arm. We believe that for those participants, the trunk was fixed to serve as a stable platform from which the arm could be controlled. Five of the participants had a much larger r^2, which indicated that the adaptations in the hip were related to the adaptations in the arm.

How were the synergies we found in reaching with rods related to the synergies yielded in reaching with just the arm? When studying participants reaching without a tool, Ma and Feldman (1995) found two synergies: One constituted the arm and produced the hand movement to the target, and the

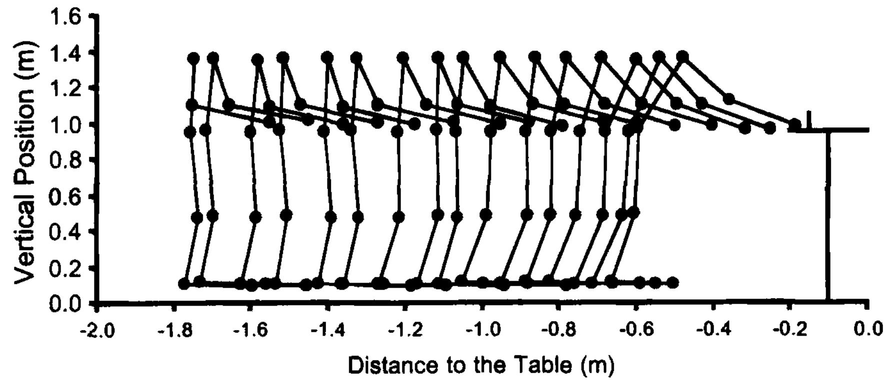

FIGURE 2. The averaged posture of Participant 3 is shown for the different rod lengths. The posture with the smallest reaching distance belonged to rod length zero, whereas the posture with the largest reaching distance belonged to the longest rod. Each dot is a value averaged over 10 repeated measures. The dots represent the toe, ankle, knee, hip, shoulder, elbow, and wrist of the right side of the body.

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TABLE 3
Regression Analyses Between Shoulder Angle and Elbow Angle in Experiment 1

Participant	Intercept	Slope	*F*	*df*	r^2
1	−116.26	0.97	172.25	1, 151	.53
2	−150.64	1.21	415.57	1, 148	.74
3	−107.98	0.94	1,002.09	1, 150	.87
4	−83.39	0.79	208.04	1, 153	.58
5	−131.38	0.97	394.34	1, 153	.72
6	−142.17	1.22	385.08	1, 155	.71
7	−150.03	1.24	833.54	1, 150	.85
8	−159.98	1.37	543.28	1, 149	.78
9	−44.69	0.43	117.44	1, 154	.43

Note. $p < .001$ for all of the regression equations.

other was between the trunk and the arm but did not affect the endpoint of the arm. Our findings, when participants used rods that varied in length, were somewhat different; we found evidence that the arm (i.e., shoulder angle and elbow angle) was organized as a synergy but that for about half of the participants, the trunk was not coupled to the arm.

To examine how the posture was adapted to rod length, we performed separate ANOVAs on the ankle, knee, hip, shoulder, and elbow angles. Only the analyses on ankle, $F(1, 8) = 13.00, p < .01$, shoulder, $F(1, 8) = 27.50, p = .001$, and elbow, $F(1, 8) = 72.46, p < .001$, angles showed significant linear contrasts. The means are presented in Table 1, and all effects are visible in Figure 2. For ankle angle, the shank was more upright for longer rods. The shoulder angle effect was that, with longer rods, the elbow was closer to the body. The elbow, in turn, was more bent for longer rods. The leg and trunk, it seems, were not systematically adjusted, which means that the orientation of the body to the ground was regulated in the ankle.

To summarize, we saw that reaching distance, arm posture, and ankle angle changed systematically with rod length. All participants seemed to organize the shoulder and elbow as a synergy. For about half of the participants, the hip formed a synergy with the shoulder and elbow. What were the origins of those adaptations? The adaptations in reaching distance and arm angles—and also the formation of the synergies, for that matter—might reflect a common response to manipulation of a single variable. Other possibilities are that adaptations of reaching distance and posture are influenced by different variables or that one adaptation follows from the other. We hypothesized in the introduction that the reachable distance depends on both the geometrics and the dynamics of the body + rod system. If only the geometrics determine the behavior, no postural adaptations would be expected; changes in distance would relate one-to-one to changes in rod length. However, posture was adapted, which raises the question of whether the adaptations stemmed from dynamics. To address that issue, we varied dynamics characteristics independently of the length in Experiments 2 and 3 by varying the rod's mass and mass distribution. Moreover, length, mass, and mass distribution of the rod are expected to affect how wieldable the rod is, which might be important for the displacement of the object. Therefore, those rod characteristics were also manipulated.

EXPERIMENT 2

The results of Experiment 1 revealed that reaching behavior was adapted to rod length and that functional synergies in the arm controlled the rod. We noted that the geometrics of the system were not the sole determiners of the reaching behavior; posture was also affected by rod length. That observation suggests either that participants failed to accurately detect the geometrical properties and had to make up the difference posturally or that kinetic properties

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TABLE 4
Regression Analyses Between Hip Angle and Shoulder and Elbow Angles in Experiment 1

Participant	Intercept	Shoulder angle slope	Elbow angle slope	F	df	p	r^2
1	12.40	0.21	–0.07	20.05	2, 150	.001	.21
2	21.31	0.47	–0.20	130.37	2, 147	.001	.64
3	20.91	0.41	–0.17	80.12	2, 149	.001	.52
4	1.80	0.36	–0.05	164.76	2, 152	.001	.68
5	1.72	0.07	–0.07	1.58	2, 152	.210	.02
6	10.55	0.37	–0.10	202.62	2, 154	.001	.72
7	19.37	0.50	–0.20	202.90	2, 149	.001	.73
8	529.98	–0.02	–3.85	20.26	2, 148	.001	.21
9	14.20	0.00	0.00	0.02	2, 153	.980	.00

were independently important. In Experiment 2, we manipulated, in addition to length, the homogeneous mass of the rods. That manipulation enabled us to study kinetic effects independently of length.

The participants' task was to make a comfortable reach; thus, the stopping distance should have accommodated the length of the rod and allowed for a comfortable posture. That procedure means that the to-be-adopted posture should be reflected in the chosen stopping place. Manipulating both length and mass allowed us to tease apart the relative contributions of information about length and information relevant to posture. There were two distinct sources of information: the obvious visual information about length but, in addition, the information from dynamic touch. Changing length and mass affects muscle and tendon deformations relevant to holding and manipulating a rod, which characterizes the haptic subsystem of dynamic touch (Gibson, 1966; Turvey & Carello, 1995). Through the subsystem of dynamic touch, a variety of rod characteristics (e.g., length, wieldability, flexibility, required force) might be detected. The subsystem might use some of those properties to constrain posture; others might constrain stopping location. In the following, we speculate on the possible importance of haptically perceived length, moments of inertia, torque produced by the rods, and compensation of the shift in center of mass.

Perhaps haptically perceived rod length constrains the reaching distance independently of postural constraints. A series of experiments strongly suggest that the principle moments of inertia of an object are detected via dynamic touch (Solomon & Turvey, 1988; for an overview, see Turvey & Carello, 1995). Moments of inertia reflect the extent to which an object resists rotational acceleration; they depend on the size, mass, and mass distribution of an object. The results of several studies within the dynamic touch paradigm have shown that both the major (perpendicular to the longitudinal axis of the rod) and the minor (along the longitudinal axis of the rod) moments of inertia (I_1 and I_3, respectively) are important for haptically perceived length. In a series of experiments in which the relation between different rod properties and reported length was investigated, Fitzpatrick, Carello, and Turvey (1994) revealed the relation between haptically perceived length (HPL) and the moments of inertia of the hand-held rod: HPL = $3.8 * I_1^{0.41} * I_3^{-0.30}$. In one of the experiments on which that relation was based, Fitzpatrick and her colleagues found that heavier rods (i.e., rods with larger moments of inertia) that are held but not seen are perceived as longer than lighter rods of equal length (Carello, Fitzpatrick, Flascher, & Turvey, 1998; Fitzpatrick et al., 1994). For us, such a finding would mean that if haptic information about rod length alone determines the action, then a larger distance to the table would be selected with heavier rods.[2]

Posture, which we expected to be determined by the dynamics of the body + rod system, also ought to be affected by the moments of inertia. One possible relation can be termed *wieldability*. In our experiment, once a stopping place had been selected, the rod was lowered and moved sideward to displace the object. The effort required to change rotational velocity of the rod is captured by the moments of inertia about the axes of movement. The resistance relevant to the lowering movement (in the sagittal plane) corresponds to the largest moment of inertia (I_1), whereas the resistance to the sideward movement (in the transverse plane) corresponds to the intermediate moment of inertia (I_2). A long and heavy rod has larger I_1 and I_2, so more muscular effort is required to change the movement direction than to wield a short and light rod. That change in required muscular effort might demand a postural adaptation. Such effects of moments of inertia on posture should be independent from the haptically perceived length.[3]

Increasing the homogeneous mass of a rod increases forces and torques above and beyond that related to length of the rod. Participants might use several strategies to counteract the torques produced by the rods, of which we name the following three: (a) avoiding reaching maximum joint moments, (b) keeping the torque in a certain joint constant over a range of rods, and (c) minimizing the torque in one or more joints. As to avoiding the maximum joint moments, Chaffin and Andersson (1991) presented equations that predict joint-moment strength in any given posture. For each joint, one can compute the expected maximal muscle-produced joint moment that can counteract moments created by external loads. Using those formulas, we modeled our task and found that if relatively heavy rods have to be handled, the shoulder must be retroflexed (upper arm behind the shoulder) and the elbow moderately flexed. To see whether participants used any of the other strategies mentioned, we computed the (sagittal plane) torques in the joints in question. It is important to note that all of the strategies require a postural adaptation, because the torques produced by the rods increases with increasing length and mass.

Lowering a rod is biomechanically similar to extending an arm, because the body center of mass (CM) is shifted outward in both cases. Participants might adjust the posture to compensate for that shift. Several researchers have measured postural adjustments and muscle activity before and after the start of fast shoulder flexions that brought an arm at the side to the horizontal (Aruin & Latash, 1995; Bouisset & Zattara, 1981, 1987; Brown & Frank, 1987; Horak, Esselman, Anderson, & Lynch, 1984; Lee, 1980; Lee, Buchanan, & Rogers, 1987; Van der Fits, Klip, Van Eykeren, & Hadders-Algra, 1998; for an overview, see Massion, 1992). In general, those authors have reported an increase in electromyographic (EMG) activity of the postural muscles of the back, which results in a displacement of the CM opposite to that expected from the arm movements. Moreover, the postural muscles were activated before or in an early phase of the arm movement (depending on condition), which suggests that the activity had an anticipatory component. If load was varied, then the EMG activity increased or the onset of the anticipatory activity was moderated, depending on condition (Aruin & Latash, 1995; Bouisset & Zattara, 1987). Those findings imply that picking up a rod would yield a posture in which the body CM is more posterior and that the effect would be larger for rods that produce a larger torque. That hypothesis is also consistent with experimental findings that maximum acceptable load decreases with increasing distance to the load (Ciriello, Snook, & Hughes, 1993; Garg, 1989). Therefore, we expected that participants would select a closer distance to the table when they used longer and heavier rods.

In sum, on the basis of haptically perceived length, we expected a greater distance to the table with heavier rods. From findings regarding the way a heavier rod affects the posture, however, we expected a closer distance to the table to be selected with heavier rods. That difference should make it relatively easy to evaluate the importance of the two sources of information. A manipulation of variables related to wieldability was deferred until Experiment 3.

Method

The method of Experiment 1 was followed; any deviations are indicated.

The 22 participants (14 women and 8 men) ranged in age from 18 to 42 years. Rods with a diameter of 1.25 cm were used; they ranged in length from 0.1 to 1.0 m, in 0.1-m steps. Three sets of 10 rods were constructed, one set from wood (density = 0.67 g/cm^3), one from aluminum (density = 2.70 g/cm^3), and one from steel (density = 7.80 g/cm^3). A handle was added to each rod, extending it by 11.5 cm. A small disc separated the handle from the rod. Moreover, a small plastic tube was put over the handle part of the rod. We painted all rods white to prevent the participants from seeing the difference in material. Characteristics of the rods (e.g., length, mass, and moments of inertia) are presented in Table 5.

We calculated a variety of variables to see which one best predicted reaching distance and posture. We computed the three moments of inertia of the rod with the rotation point in the wrist (to simplify the computations, we neglected the mass of the hand). To compute the haptically perceived length, we used the following formula of Fitzpatrick et al. (1994): HPL = 3.8 * $I_1^{0.41}$ * $I_3^{-0.30}$. The static moment, which is the invariant part of the static torque (Kingma, Beek, & Van Dieën, 2002), was computed as the distance between the wrist and the CM of the rod multiplied by the gravitational acceleration and the mass of the rod.

We also calculated the torque acting in the joints at the start of cylinder displacement. To do so, we used participants' anthropometric measures to compute the CM of the (compound) segment acting on a joint. For instance, for computing the torque around the elbow, we used the rod, hand, and forearm. The positions of the arm and the orientation of the rod at the moment the object started to be displaced were used. We multiplied the horizontal distance between the CM and the joint by the gravity force (the sum of the segment masses times gravitational acceleration). The torque varied with the orientation of the joints and the rod. The torque acting in a clockwise direction was labeled *normal.*

Each participant was tested in one session. There were 33 conditions: for each of the three rod-types, a set of 10 rods and one control condition (the tip of the fingers). Each condition was presented six times in randomized blocks, for a total of 198 trials for each participant. Of the total of 4,356 trials, 31 were omitted because a residual of the regression analyses exceeded the threshold.

Results and Discussion

Reaching Distance

We analyzed reaching distance by using a two-way multivariate ANOVA, with rod type (wood, aluminum, and steel) and rod length as within-participant factors. The analysis was performed on the averages for each participant and each condition. The averages over participants for the levels of the significant variables in this experiment are presented in Table 6. The main effect of rod type was significant, $F(2, 20) = 5.26$, $p < .05$, $\eta^2 = .35$[4]; when reaching with heavier rods, participants selected a distance closer to the table. The main effect of rod length was also significant, showing, as expected, that participants stopped farther from the table when they used

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TABLE 5
Characteristics of Rods Used in Experiment 2

Rod length (m)	Rod mass (g)	I_1	I_2	I_3	Static moment (Nm)	HPL
			Wood rods			
0.1	0.014	0.27	0.26	0.011	0.017	4.02
0.2	0.021	0.76	0.74	0.017	0.034	5.34
0.3	0.027	1.66	1.64	0.024	0.058	6.71
0.4	0.034	3.11	3.08	0.030	0.088	8.10
0.5	0.040	5.23	5.19	0.036	0.124	9.48
0.6	0.047	8.16	8.12	0.042	0.167	10.85
0.7	0.053	12.02	11.98	0.048	0.216	12.22
0.8	0.060	16.96	16.90	0.054	0.272	13.58
0.9	0.067	23.09	23.03	0.061	0.334	14.93
1.0	0.073	30.56	30.49	0.067	0.402	16.28
			Aluminum rods			
0.1	0.063	1.20	1.15	0.049	0.076	4.73
0.2	0.092	3.39	3.31	0.078	0.153	6.30
0.3	0.122	7.43	7.32	0.107	0.258	7.92
0.4	0.151	13.90	13.77	0.134	0.392	9.55
0.5	0.180	23.39	23.23	0.162	0.554	11.17
0.6	0.210	36.49	36.31	0.189	0.746	12.80
0.7	0.239	53.79	53.58	0.217	0.966	14.41
0.8	0.268	75.86	75.62	0.244	1.215	16.01
0.9	0.298	103.31	103.04	0.271	1.492	17.61
1.0	0.327	136.70	136.41	0.298	1.799	19.19
			Steel rods			
0.1	0.192	3.65	3.51	0.149	0.232	5.35
0.2	0.281	10.32	10.09	0.239	0.465	7.11
0.3	0.371	22.62	22.30	0.326	0.786	8.94
0.4	0.460	42.33	41.93	0.411	1.193	10.78
0.5	0.549	71.25	70.76	0.495	1.688	12.62
0.6	0.639	111.15	110.58	0.578	2.271	14.45
0.7	0.728	163.82	163.17	0.661	2.942	16.28
0.8	0.817	231.06	230.33	0.744	3.700	18.09
0.9	0.907	314.64	313.83	0.827	4.546	19.89
1.0	0.996	416.36	415.47	0.910	5.479	21.68

Note. Moments of inertia I_1, I_2, and I_3 were measured in kgm^2 * 10^3. HPL = haptically perceived length.

longer rods, $F(10, 12) = 187.24$, $p < .001$, $\eta^2 = .99$. The interaction was not significant. The means in Table 6 revealed that a larger distance was selected in the no-rod condition than in the shortest rod condition. On the one hand, that finding might indicate that even the shortest rod adds enough torque to require an adaptation. On the other hand, it might indicate that participants select the distance differently when they are holding a rod.

As to the basis for those effects, one suggestion is that haptically detected information about rod length affected the stopping place. If that were so, the chosen distance from the table would have been larger for heavier rods, because the haptically perceived length of heavier rods is longer than that of lighter rods of equal physical length (Carello et al., 1998; Fitzpatrick et al., 1994). That in the present experiment a shorter distance was selected with heavier rods suggests that the haptically perceived length contributes little or nothing to determining the reaching distance in a situation in which visual information is available.

Previous experiments have shown that anticipatory postural adjustments to counteract movement-related CM shifts are larger for heavier loads. We therefore had predicted that posture would be more upright (less forward-leaning) for the heavier rods, which, if anticipated, would result in a closer distance to the table. That adjustment in the reaching distance was indeed found. Examining the postural adapta-

TABLE 6
Means and Standard Deviations for the Significant Effects of the Analyses of Variance in Experiment 2

Rod characteristics	Reaching distance (m)		Shoulder angle (deg)		Elbow angle (m)	
	M	*SD*	*M*	*SD*	*M*	*SD*
Type						
Wood	0.73	0.28	11.40	13.55	140.81	13.59
Aluminum	0.73	0.27	10.28	14.00	139.01	13.87
Steel	0.72	0.27	7.94	14.69	136.73	14.22
Length (m)						
0.0	0.40	0.17	19.65	14.02	146.87	12.04
0.1	0.39	0.11	18.25	13.92	147.49	13.23
0.2	0.48	0.10	16.40	13.17	145.52	12.86
0.3	0.55	0.10	14.17	12.64	142.79	12.41
0.4	0.63	0.10	11.32	12.72	140.24	12.79
0.5	0.72	0.10	9.03	11.84	138.02	12.50
0.6	0.80	0.10	6.90	11.95	135.70	12.97
0.7	0.88	0.10	5.18	12.21	134.63	13.10
0.8	0.97	0.10	3.32	11.93	132.85	12.90
0.9	1.06	0.09	2.57	12.22	132.50	12.85
1.0	1.14	0.09	0.96	12.55	130.75	12.89

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tions, which we do in the next subsection, should make clear whether the effects on distance were the result only of the more upright posture or whether forces and torques in the arm joints contributed.

Posture

To examine postural effects, we first determined whether synergies were formed in the arm or between the trunk and the arm. As in Experiment 1, we used regression analyses to discover which postural angles were related. We started by regressing shoulder angle on elbow angle. An analysis on the data of all participants together revealed that adjustments in shoulder angle corresponded to adjustments in elbow angle: shoulder angle = 0.79 * elbow angle – 99.71, $F(1, 4323) = 6{,}770.27$, $p < .001$, $r^2 = .61$. That pattern was confirmed by the analyses on the individual participants: Two participants showed a weak correspondence between the two angles (i.e., r^2 of .19 and .30), but for the other 20, the correspondence between the two angles was considerably stronger, with r^2 ranging from .48 to .89. We conclude that the angles in the arm reflected a synergy. Note, however, that the percentage of explained variance was smaller than we had seen in Experiment 1.

To examine the relation between trunk and arm, we performed a multiple regression, with hip angle as the dependent variable and shoulder and elbow angles as the independent variables. The analyses on the data of individual participants showed that for 4 of the 22 participants, the correspondence between those angles was moderate (r^2 of .62, .55, .50, and .44). For the remaining 18 participants, the r^2 ranged from .01 to .32, indicating that, in general, the adjustments in the hip for the majority of the participants tended to be independent from the adjustments in the shoulder and elbow. The lack of a systematic relation was also evident in the pooled data: Hip angle = 29.90 + 0.22 * shoulder angle – 0.24 * elbow angle, $F(2, 4322) = 260.83$, $p < .001$, $r^2 = .11$. That analysis showed that the trunk organization was not strongly related to adjustments in the arm. That finding might suggest that the trunk served as a stable platform from which the arm could be controlled, a thesis to which we return after considering how the posture depended on variations in rod length and mass.

Separate ANOVAs were performed on ankle, hip, shoulder, and elbow angles (given the nonsignificance of the knee angle in Experiment 1, that angle was not expected to be of importance for the present task). Two-way multivariate ANOVAs were performed with rod type (wood, aluminum, and steel) and rod length as within-participant variables. The averages for the levels of the significant main effects are presented in Table 6. Ankle and hip angles showed no significant effects. As to shoulder angle, the main effect of rod type was significant, $F(2, 20) = 18.20$, $p < .001$, $\eta^2 = .65$; the shoulder was more anteflexed with lighter than with heavier rods; that is, with lighter rods, the elbow was more anterior to the shoulder. The main effect of rod length was also significant, showing that with longer rods the shoulder was less anteflexed, $F(10, 12) = 5.69$, $p < .005$, $\eta^2 = .83$. As to elbow angle, the main effect of rod type was significant, $F(2, 20) = 16.56$, $p < .001$, $\eta^2 = .62$; the elbow was more extended with lighter than with heavier rods. The main effect of rod length was also significant, showing that with shorter rods, the elbow was more extended, $F(10, 12) = 9.12$, $p < .001$, $\eta^2 = .88$.

Taken together, the results of the angle analyses showed that only the arm was adapted to changes in length and mass

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of the rod. The leg and hip joints were not adjusted. Remember that we predicted from the literature on anticipatory postural adjustments that posture would be more upright for the larger loads. We did not, however, find such an effect; a similar posture in the leg and trunk was used in all conditions. A single lower-body posture would provide a stable platform, allowing the angles in the arm to be varied to make the displacement. The adjustments in the arm showed that with longer and heavier rods, the arm was held closer to the body and the elbow was more flexed. Such a posture is consistent with the literature about people lifting loads. The acceptable load has been found to be higher when the distance to the load is larger (Ciriello et al., 1993). From that finding, we expected that participants might bend the arm to decrease the distance to the heavy rod, and, indeed, heavier loads were held closer to the body. That observation might mean that the torque produced by the rods is critical to arm adjustments. In our final analyses, we focused on whether the adaptations in the distance and the posture stemmed from the torque the rods produced.

Torques

One of our goals in our torque analysis was to evaluate whether the adaptations in the shoulder and elbow stemmed from minimizing torque or from avoiding maximum torque in one of those joints. We computed the torque that acted in those joints at the moment the object was displaced. To estimate the maximum joint-moment strengths for the observed postures, we used the equations of Chaffin and Andersson (1991, pp. 250–251). The predicted maxima were much larger than the actual torques arising in the participants' task execution. From that simple fact, we conclude that participants avoided moments that they would not be strong enough to sustain.

The torque produced by a homogenous rod depends on its length, mass, and orientation. Note that in our experiments, the orientation of the rod was always similar during displacement, that is, horizontal. Participants could adapt the posture to modulate the torque in the joints that a certain rod produced. For instance, a posture with the elbow and hand behind the shoulder while the rod is horizontal would minimize the torque in the shoulder for all the rods we used in our experiment. Did participants adapt the posture to minimize the torque in one of the joints? In Figure 3, we plotted how the torque in the wrist, elbow, and shoulder depended on the length and mass properties of the rod. To compute the torque, we used the orientations of the arm and the rod at the moment the object started to be displaced. The torque in the wrist was larger for longer and heavier rods, essentially following the pattern of the torque produced by the rod alone. A similar pattern was observed for the torque in the elbow. The values were larger for the torque in the elbow than for the torque in the wrist because of added torque produced by the forearm. The torque in the shoulder was also larger for rods that could create larger torques (i.e., longer and heavier rods), and it was larger than the torque in the elbow because of the torque that the upper arm produced. Note that adaptations in the arm posture could particularly affect the torque in the shoulder. Nevertheless, the torques created by the rod showed up at the elbow and shoulder, something one would not expect if posture were compensating for that torque by reducing the torque created by the limb segments. That finding led us to believe that participants did not adjust the posture to decrease the torques in the joints. In other words, the posture was not adapted to minimize the torques in the joints.

The deviation from the increasing pattern for the torque in the shoulder when the wooden rods were used was peculiar (Figure 3). Because the wooden rods were the lightest, there was no reason to believe that the decreasing relation resulted from the torque that those rods produced. Together, the torque relations indicated to us that a variable other than torque was important in the present task.

To summarize, both rod length and mass determined reaching distance: With longer rods a longer distance and with larger mass a closer distance to the table was selected.[5] The effect of rod length was consistent with what we expected. Moreover, the results showed that the reaching distance

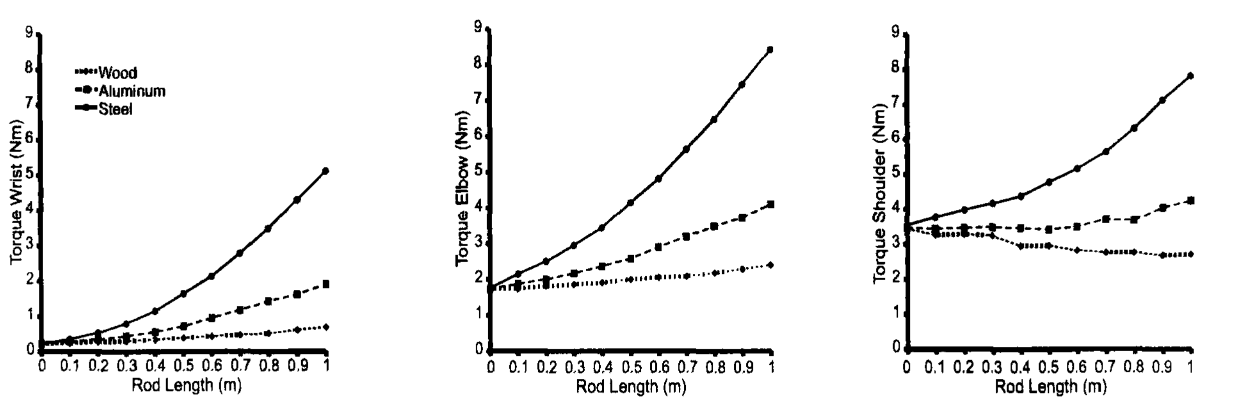

FIGURE 3. The relation between the rod properties and the torques acting in the different joints in the sagittal plane for Experiment 2.

was not in accordance with predictions related to the haptically perceived length. The mass effects on reaching distance seemed to stem from constraints that affected the posture; however, examining the relation between the torque in the joints and the properties of the rod revealed that the torque was not minimized but was increased with longer and heavier rods. To control the rod, the motor system organized the shoulder and the elbow as a synergy; if the shoulder was less anteflexed, the elbow was more flexed, and that posture occurred more for the long and heavy rods. None of the lower joints varied with rod properties, indicating that a similar posture provided stability for all the rods and that a more upright posture to compensate for the larger shift in CM for the heavier rods was not found. In the introduction to this experiment, we suggested that the wieldability of the rod might affect the posture with which the rod is controlled during the displacement. That possibility might be consistent with our finding that only the arm posture was adapted to variations in the rod; the posture in the rest of the body provided for a stable platform on the basis of which the arm could be configured to control the rod. In Experiment 3, we modified the mass distribution of the rods to examine the explanatory value of the wieldability. A difference in reaching behavior between rods with homogeneously distributed masses and rods with nonhomogeneously distributed masses would help us track down the precise characteristics of relevance. Therefore, in Experiment 3, mass distribution of the rods was also varied.

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EXPERIMENT 3

We designed Experiment 3 to evaluate the relative importance of the wieldability of the rods. We manipulated length, mass, and mass distribution, which all affect (information about) the geometrics and dynamics of the reaching system. To manipulate mass distribution, we used hollow tubing in which weights could be inserted in the tip or the handle. Rods with weight at the tip, like the heavy rods of Experiment 2, displace the CM of the body + rod system the most. They also produce more torque. The difference between the rods used in Experiment 2 and those used in Experiment 3 was in the location of the CM within the rod. With a homogeneous mass distribution, rods of any length or mass have their CM at the midpoint. However, the location of the CM in rods with nonhomogeneous mass distribution depends on the position of the inserted mass. The position of a rod's CM might be of importance for how it can be used to displace an object. For example, and with other things being equal, a rod with a heavy tip could gather more momentum at the tip. Perhaps that momentum would make it easier to smash an object off the table (cf. Beak, Davids, & Bennett, 1999; Wagman & Carello, 2001). Furthermore, and perhaps more important for the task at hand, more weight at the tip provides for more stability at the tip—because it resists tip movement more—which might require a type of control different from that needed for a rod less stable at the tip (i.e., a rod with weight at the handle). Both aspects might require postural adaptations for effective control. Note that the constraints originating from the shift in CM or the increase in torque entailed by rods with weight at the tip should be similar to those entailed by steel rods. Thus, we expected that participants would select a distance relatively closer to the table when using a rod weighted at the tip. Any deviations from that pattern might result from the aspects related to the rod's wieldability or to its stability at the tip. Any differences between the results of Experiment 2 and Experiment 3 would reveal the relative importance of that stability and wieldability.

Method

Participants (10 women and 7 men) ranged in age from 19 to 23 years. We used fewer rod lengths to keep the experiment to one session. Also, to make the experiments comparable, we chose geometric and dynamic rod characteristics that fell in the same range as the rods used in Experiment 2. Twenty-five rods were used. There were five lengths, ranging from 0.4 to 0.8 m, in 0.1-m steps. The rods were made of steel tubing (diameter = 1.6 cm). To manipulate mass and mass distribution, we built one or two 82-g lead weights into the tube. Five types of rods were constructed that way: rods with no extra mass, rods with one mass in the handle, rods with one mass at the tip of the rod, rods with two masses in the handle, and rods with two masses at the tip. The rod properties we computed for Experiment 2 were also computed for the rods in this experiment and are presented in Table 7. Each rod had a handle of 11.5 cm. The steel tube was put in a PVC tube with an outer diameter of 1.8 cm. A small plastic disc divided the handle from the rod. The part of the tube designated as the rod was painted white. Each of the 25 rods was presented six times in randomized blocks, for a total of 150 trials per participant, run in a single session. On 16 of the 2,250 trials, the *SD* of the residual exceeded the threshold. Those trials were omitted.

Results and Discussion

Reaching Distance

Reaching distance was analyzed by means of a two-way multivariate ANOVA, with rod type (no weight, one weight in handle, one weight at tip, two weights in handle, and two weights at tip) and rod length (0.4, 0.5, 0.6, 0.7, and 0.8 m) as within-participant variables. The averages and standard deviations are shown in Table 8. The main effect of rod type was significant, $F(4, 13) = 4.53$, $p < .05$, $\eta^2 = .58$. A larger reaching distance was chosen for rods with weight at the tip than for rods with no weight or with weight at the handle (see Table 8). That interpretation of the means was confirmed with a multivariate ANOVA with mass (one or two), place of weight (handle or tip), and rod length as within-participant variables. The usual main effect of rod length, $F(4, 13) = 214.69$, $p < .001$, $\eta^2 = .99$, was found. The results showed that participants selected a relatively larger distance to the table with longer rods and with rods with a weight in the tip. As with rods with larger mass, rods with weight at the tip produced more torque in the joints (see Figures 3 and 4). Contrary to the results of Experiment 2, the results of

TABLE 7
Characteristics of Rods Used in Experiment 3

Rod length (m)	Rod mass (g)	I_1	I_2	I_3	Static moment (Nm)	HPL
			No weight			
0.4	0.242	22.30	22.09	0.628	0.628	9.90
0.5	0.289	37.53	37.28	0.274	0.889	11.59
0.6	0.336	58.55	58.25	0.320	1.196	13.28
0.7	0.383	86.29	85.95	0.366	1.549	14.95
0.8	0.431	121.71	121.32	0.412	1.949	16.61
			One-weight handle			
0.4	0.325	22.71	22.27	0.463	0.666	8.06
0.5	0.372	37.94	37.44	0.520	0.925	9.60
0.6	0.419	58.96	58.41	0.574	1.231	11.17
0.7	0.466	86.71	86.11	0.626	1.583	12.75
0.8	0.513	122.12	121.47	0.676	1.981	14.33
			One-weight tip			
0.4	0.325	41.76	41.53	0.257	1.019	12.35
0.5	0.372	65.75	65.46	0.307	1.360	14.10
0.6	0.419	97.16	96.83	0.356	1.748	15.82
0.7	0.466	136.95	136.57	0.405	2.181	17.53
0.8	0.513	186.05	185.63	0.453	2.661	19.21
			Two-weights handle			
0.4	0.409	23.84	23.26	0.605	0.758	7.58
0.5	0.456	39.07	38.41	0.688	1.015	8.94
0.6	0.503	60.09	59.35	0.761	1.320	10.34
0.7	0.550	87.83	87.04	0.827	1.671	11.79
0.8	0.597	123.25	122.39	0.889	2.068	13.26
			Two-weights tip			
0.4	0.409	56.88	56.63	0.260	1.369	13.96
0.5	0.456	88.76	88.48	0.312	1.792	15.87
0.6	0.503	129.77	129.44	0.363	2.262	17.71
0.7	0.550	180.84	180.46	0.414	2.778	19.51
0.8	0.597	242.91	242.48	0.464	3.340	21.27

Note. Moments of inertia I_1, I_2, and I_3 were measured in kgm^2 * 10^3. HPL = haptically perceived length.

Experiment 3 showed that participants selected a larger distance to the table when the torques produced by the rods were larger.[6] Given that the rods used in Experiments 2 and 3 had differently located CMs, the different results seem to suggest that, independent of the forces and torques produced, participants needed more "room" to displace the object with a rod with a weight in the tip. An analysis of the joint angles might provide a fuller picture of that effect.

Posture

To determine whether the arm was organized as a synergy, we regressed the shoulder angle against the elbow angle. The analyses on the data of individual participants showed that some participants had a weak correspondence between the arm angles and others had a strong correspondence (r^2 ranging from .31, .35, .37, and .38 to .78, .79, and .84). Most of the individual participants organized the elbow and shoulder angle as a synergy. However, that pattern was not that strong for the regression analysis on the data of all the participants pooled; shoulder angle = 0.70 * elbow angle − 84.77, $F(1, 2{,}532) = 1{,}754.70$, $p < .001$, $r^2 = .41$. The coefficients of the regression line showed a correspondence between shoulder and elbow angle that was comparable with what we found in Experiment 2. However, the explained

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TABLE 8
Means and Standard Deviations for the Significant Effects of the Analyses of Variance in Experiment 3

Rod characteristics	Reaching distance (m)		Shoulder angle (deg)		Elbow angle (deg)	
	M	*SD*	*M*	*SD*	*M*	*SD*
Type						
No weight	0.82	0.13	10.85	10.93	136.91	9.96
One-weight handle	0.82	0.13	10.79	11.29	137.31	10.76
One-weight tip	0.83	0.14	11.16	11.44	136.61	10.24
Two-weight handle	0.82	0.14	11.22	11.01	137.85	10.28
Two-weight tip	0.83	0.14	10.69	11.75	136.01	10.40
Length (m)						
0.4	0.67	0.08	16.10	10.82	141.42	9.41
0.5	0.75	0.08	14.01	10.34	139.66	9.42
0.6	0.82	0.08	10.38	9.96	136.42	9.29
0.7	0.89	0.08	8.16	10.92	134.66	9.96
0.8	0.98	0.09	6.07	11.28	132.52	10.97

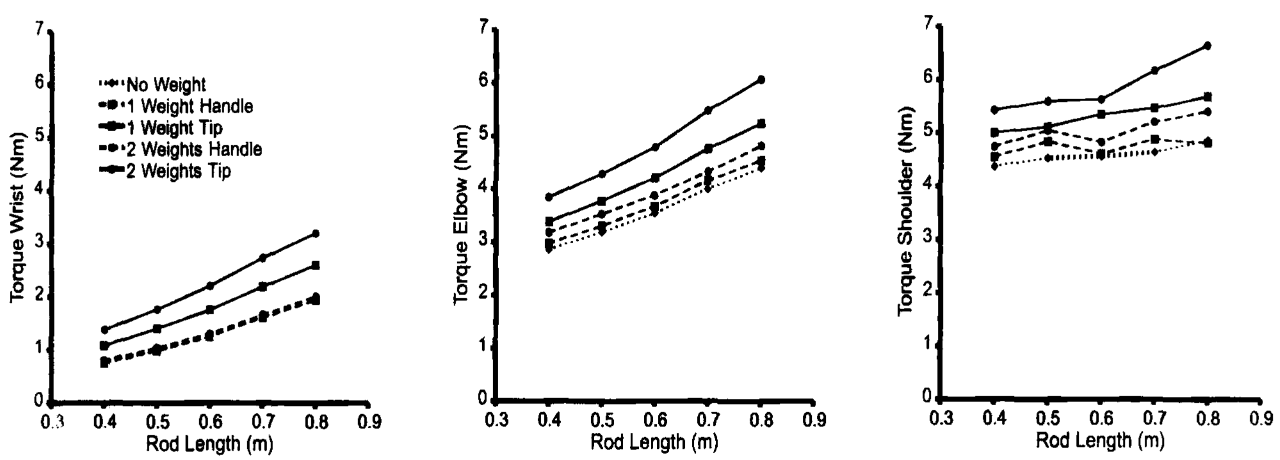

FIGURE 4. The relation between the rod properties and the torques acting in the different joints in the sagittal plane for Experiment 3.

variance of the regression line was smaller than in Experiment 2, indicating that the synergy between the arm angles was less stable. That observation might suggest that to control rods with different mass distributions, the participants perturbed the synergy in the arm. We address that aspect further after we discuss the synergy between hip and arm.

To examine the relation between hip and arm, we performed a multiple regression, with hip angle as the dependent variable and shoulder and elbow angles as the independent variables, both of which were entered at once. The analyses done for each individual participant showed that for none of the participants was the explained variance larger than .30. That means that the adjustments in the hip were independent from the adjustments in the shoulder and elbow.

To test how posture was affected by length and mass distribution, we analyzed the angles in the body by means of two-way repeated-measures ANOVAs with rod type (no weight, one weight in handle, one weight at tip, two weights in handle, and two weights at tip) and rod length (0.4, 0.5, 0.6, 0.7, and 0.8 m) as within-participant variables. As in Experiment 2, only shoulder and elbow angles systematically depended on length and mass. The only significant effect for shoulder angle was rod length, $F(4, 13) = 14.35$, $p < .001$, $\eta^2 = .82$; the shoulder was less anteflexed with longer rods. As to elbow angle, the main effect of rod type was significant, $F(4, 13) = 7.60$, $p < .005$, $\eta^2 = .70$; the elbow was more flexed for rods with weight at the tip. The usual main effect of rod length, $F(4, 13) = 9.80$, $p = .001$, $\eta^2 = .75$, was also found; the elbow was more flexed with longer rods. The interaction was not significant.

The adaptations in the angles revealed that, as in Experiment 2, only the arm was adapted to changes in length and

TABLE 9
Intercorrelations Between the Independent Variables Significant in the Multiple Regression Analysis

Variable	1	2	3	4	5	6
1. Rod length	—	−.29**	−.02*	−.03*	−.28**	.39**
2. Upper arm length		—	.19**	.08**	.99**	.31**
3. Body mass			—	−.10**	.23**	.05**
4. Body height				—	.10**	.03**
5. Lower arm length					—	.32**
6. Static moment						—

*$p < .05$, two tailed. **$p < .01$, two tailed.

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mass properties of the rod. Note that the maximum torque that a rod could produce increased with its length, mass, and the mass more at the tip. To test whether postural adaptations minimized the torques in the joints, we plotted the torques in the wrist, elbow, and shoulder for the different rods used in this experiment (see Figure 4). As can be seen, the torque in the arm joints systematically increased with longer rods, with larger mass, and with mass more at the tip. From that torque increase it followed that participants did not adjust the posture to compensate for the larger torques that the rods produced. Therefore, we conclude that, as in Experiment 2, participants did not adjust the posture to minimize the torque in one of the arm joints when displacing the object on the table with the tip of the rod.

To summarize, in the present experiment, the adaptations in the posture were confined to the arm, which was organized as a synergy independent from the hip, and the torque was not minimized. The postural adaptations were remarkably similar for the two experiments. In that light, it is even more peculiar that a larger distance to the table was selected for a rod with weight at the tip, whereas a smaller reaching distance was selected with relatively heavier rods. Varying the mass distribution affected the location of the CM on the rod and, thus, the momentum that could be produced at the tip and the inertia of the tip. However, varying the mass distribution did not seem to affect the postural adaptations made to control the rod; that is, for rods that produced more torque in the joints, the elbow was more bent, independent of the precise origin of that torque. That finding invites the question of whether there was a common ground for the adaptations in the distance.

Multiple Regression Model

A key issue in the present study was the basis on which participants adapted their actions. Because the experimental setup and the task to be performed were similar in all the experiments, we expected that one variable or set of variables could explain the behavior in all the experiments and, in particular, the selection of the reaching distance. To help us identify that (perhaps compound) variable, we performed a multiple regression analysis on the pooled data of Experiments 1, 2, and 3. In that analysis, all the rod properties that we thought might be of possible importance were tested (see Tables 5 and 7). Moreover, we included not only properties of the rod but also characteristics of the participants, because we expected that anthropometric differences, such as body height or arm length, also would affect the distance selected. We excluded the trials on which the object was moved with the fingers (control conditions of Experiments 1 and 2). As the dependent variable, we used reaching distance, and as independent variables, we used rod length, body mass, body height, upper arm length, lower arm length, rod mass, I_1, I_2, I_3, and static moment of the rod. The independent variables were entered with a forward stepwise procedure. The variables that significantly explained the variance in the reaching distance were (in order) rod length, upper arm length, body mass, body height, lower arm length, and static moment, $F(6, 7{,}760) = 10{,}605.56$, $p < .001$, $R^2 = .89$. The explained variance of the regression model was high, indicating the relevance of the variables. Of all the variables, rod length explained the majority of the variance (the model with only rod length as the independent variable explained 85% of the variance). However, that finding was caused by the large variation in rod length compared with the variation of other variables. As expected, the length of the upper arm correlated highly with the length of the lower arm (see Table 9). All the other variables that explained variance in the reaching distance were not correlated.

It was to be expected that anthropometrics of the individual participants would affect the selected distance. Of course, the distance reflected the length of body segments, but, more important, the distance also reflected body mass and static moment of the rod. Those latter aspects will affect the posture with which the rod can be controlled. That those variables explained parts of the variance reinforces our claim that the chosen distance is affected by the posture required to control the rod at the moment of displacement.

GENERAL DISCUSSION

In three experiments, we studied whether and how changes in rod characteristics affect aspects of participants' selecting a stopping place and making a reach to displace an object. In the different experiments, length, mass, and mass distribution of the rods were manipulated. We were interested in how those properties would affect reaching distance and the posture with which the object is displaced. In Experiment 1, wooden rods differing in length were used. The resulting reaching distance was adapted to length in a very consistent way, showing that participants were sensitive to the change in their reaching possibilities. The shoulder and elbow angles reflected a synergistic organization, and most of the adaptations in posture took place in the arm. We distinguished two broad categories of information available to the participants to perform the task: (a) information concerning the geometrics of the reaching system, related to the length of the rod, and (b) information concerning the dynamics of the reaching system, having postural consequences.

In Experiment 2, we manipulated length and (homogeneous) mass of the rods to investigate which variable or variables provided the basis for participants' adjustments. Participants selected a closer distance to the table with the heavier rods. The only postural adjustments were made in the arm, and, again, the shoulder and elbow were organized as a synergy. That finding suggested that the rest of the body, which remained independently of the properties of the rod, served as a stable platform from which the arm could be controlled. In addition, we found that participants did not adapt the posture to minimize the torque in the arm joints. To further explore which dynamic properties of the rod constrain reaching behavior, we manipulated the dynamics of the rod differently in Experiment 3, namely, through varying mass distribution.

In Experiment 3, we found that the reaching distance was relatively longer for rods with a weight in the tip, as compared with rods with weight in the handle. The organization of posture was similar to that in Experiment 2; the shoulder and elbow acted as a synergy. Moreover, participants did not make postural adjustments to minimize the torque. When comparing Experiments 2 and 3, one finding stood out: The elbow adjustment was similar (flexion) for both heavier rods and rods with mass in the tip, whereas chosen distance was adapted differently for those two rod types. It seemed that the adjustments in posture were similar, independent of the distance to the table that was selected. That finding raises questions regarding a key issue of the present article, that is, whether postural adjustments were anticipated in the selected distance.

To examine whether the distance anticipated postural adaptations, we now asked whether the reaching distance anticipated the length of the arm with which the object was displaced (i.e., the effective length), independently of the precise posture. Therefore, we performed additional analyses on the effective length that the arm posture provided. Note that variations in the reaching distance were primarily variations in the horizontal axis of the sagittal plane. The effective length provided by the arm posture was computed in the sagittal plane; we computed the distance between the projections on the horizontal axis of the wrist and the shoulder. In other words, the effective length of the arm was the horizontal distance between shoulder position and wrist position—a larger distance reflected more extension of the arm. For the two experiments in which that distance was analyzed, ANOVAs showed that the effective length of the arm was in accordance with adaptations in the distance participants selected with the foot.[7] In short, that finding indicated that the chosen distance was prospectively adapted to the posture with which the object was going to be displaced.

We searched for variables that contributed to determining the reaching distance in all three experiments. Therefore, we performed a multiple regression on the pooled data of all three experiments. In that analysis, we tested anthropometrics of the participants and a variety of rod properties for their explanatory value. Length of the rod was most important for determining the distance. Moreover, body mass and height, arm length, and static moment were significant predictors of the reaching distance. Those latter variables indicated that the dynamics of the body + rod system were of importance for the selection of the distance.

Our departure point for the reported research was that successful reaching requires the organization of the action system into a task-specific system matched to the environment. Changing the properties of tools made it possible for us to systematically vary the characteristics of the action system, which we took to include whatever implements were held. Our results showed that participants are sensitive to changes in the properties of their action system; adaptations in reaching distance depended both on geometrics and dynamics of the reaching effectivity. Regarding the geometrics of the body + rod system, we asked whether haptic information about length (cf. Fitzpatrick et al., 1994) influenced the selected distance; the behavior of the participants suggested that it did not. It seemed that the most important geometric property of the system was simply length of the rod, as specified by optical and not haptic information. Note the highly accurate changes in the distance that accompanied variations in rod length. That finding seems to conflict with reports on distance perception in which participants' accuracy in perceiving distances has been questioned (e.g., Norman, Todd, Perotti, & Tittle, 1996; Philbeck & Loomis, 1997). However, our experiments differed in two important aspects from such studies: In the present task, participants received feedback about performance on each trial, and both visual and haptic information were always available. Hence, we believe that the surplus of information made it possible for participants to choose well a distance that accommodated the geometric properties of the body + rod system.

Regarding the dynamics of the action system, we formulated hypotheses related to the shift in CM of the body + rod system (cf. Bouisset & Zattara, 1987) and the minimization of the torque, among other things. Those two aspects of the task seemed to be of particular importance, according to the literature on how reaching is accompanied by postural

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adjustments. Our participants adapted only the posture of the arm, however, whereas the posture in the rest of the body was organized independently of the rod properties. To emphasize, the properties of the rod had their primary effect on the arm that held the rod. We believe our results indicate that the body posture served as a stable platform from which the action system could organize the arm as a synergy to control the rod for the displacement. The postural adjustments required to control the rod were reflected in the distance to the table. How the adaptations in the distance can differ for the homogeneous and nonhomogeneous varied mass is an issue we turn to shortly.

How can the postural adaptations be interpreted? An important finding was that the organization of the posture is not simply constrained by the forces and torques acting in the limbs. Properties of the task—in our case, the displacement of the object—put such constraints on the action system that the torques that arise in the joints are not the limiting factor in the execution of the task. In other words, postural constraints might be subordinate to suprapostural aspects of the task. The role of postural-control facilitating suprapostural tasks has been examined in a series of experiments on postural sway (e.g., Balasubramaniam, Riley, & Turvey, 2000; cf. Riccio & Stoffregen, 1988; e.g., Riley, Mitra, Stoffregen, & Turvey, 1997). The focus in Riley et al. (1997) was on how vision and leaning in the ankles affected exploratory and performance parts of postural sway. Their results indicated that the details of postural sway depended on the constraints of the task. In our task, the organization of the lower-body posture was relatively independent of the rod, whereas the arm posture depended on the rod. We did not measure the postural sway during the act of displacement, but an examination of that sway might help us to understand the relative contribution to the stability of the synergy in the lower body and the synergy in the arm.

The results showed that the way participants act upon the environment (in our case, the object on the table) depends on the geometrics and dynamics of the body + tool system. We interpret those findings as illustrating that effectivities (and, thus, affordances) are affected not only by geometric but also by kinetic properties of the action system. That finding is in agreement with research of Konczak, Meeuwsen, and Cress (1992), who showed that the perceived climbability of stairs depends not only on leg length but also on dynamic properties of the action system, such as its flexibility and strength, which both change with age. Affordances, thus, are action scaled rather than merely body scaled, and people appear to be sensitive to that action scaling (see also Oudejans, Michaels, Bakker, & Dolné, 1996). The fact that our participants selected reaching distances in accordance with rod dynamics demonstrates that implements, too, can be integral to action scaling. The advantage of using tools for investigating action scaling is that the effectivities can be manipulated in a continuous and systematic way.

Not only did we find that tool use provides a useful inroad to studying action, but we also believe that an action perspective provides a good inroad to studying tool use. As we noted in our introduction, in earlier studies of tool use the dynamics of the action system were neglected, because their focus was on the shape of a tool that was selected given a certain task. Interest in cognitive abilities to conceive of an object of a particular shape as a tool is not likely to raise issues about the motor aspects of wielding the tool. The present findings imply, however, that one cannot come to a general understanding of tool use without acknowledging the importance of kinetics. That implication reinforces our earlier claim that tool use should be approached as an action problem instead of as a cognitive problem (cf. Lockman, 2000; cf. Smitsman, 1997; Smitsman & Bongers, in press).

We believe that our findings also have implications for models of reaching. Again, we argue that in most models, the full implications of the fact that humans often reach with a tool in their hand are not considered. The data presented here show that the dynamic characteristics of a tool are important for the organization of the act. Models such as those of Bullock, Grossberg, and Guenther (1993) and Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, and Engelbrecht (1995) simulate reaching with tools. However, the modeling is limited to geometric and kinematic characteristics; in neither model are dynamic characteristics of the tool taken into account. Our results suggest that the principles by which those models control the reach need to be elaborated if they are to account for phenomena observed in reaching with rods.[8]

We conclude with an issue that the present research left unresolved. We discussed how the results showed that the effectivity is constrained so that the relation between end-effector and environment can be regulated. However, aspects of the findings of Experiment 2 appeared to contradict the findings of Experiment 3: Heavy rods with homogeneous mass resulted in the choice of a closer distance to the table than lighter rods of the same length, whereas nonhomogeneous rods with mass at the tip resulted in the choice of a larger distance to the table. One would expect that the two rod types would put similar constraints on posture. Moreover, the postural adaptations for the rods with weight at the tip and of larger mass seem to share, at least in part, a similar basis; for both rod types, the elbow is more flexed. For now, we must leave that issue open, although we can present hypotheses regarding the seeming contradiction and suggest ways to test them in the future. An experimental setup that requires anterior–posterior movements, such as in a poking task, would provide one way for investigators to further explore how reaching distance relates to the postural adaptations to see if the same distance–posture relations emerge.

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NOTES

1. In the studies in which the occurrence of such synergies was originally addressed, the relation between the angles over time within a trial during the act of reaching was measured. In the current experiment, we measured the relation between angles at one moment in a trial. We analyzed how the synergy varied over trials.

2. We were aware of the possibilities of the limited importance of results regarding haptically perceived length revealed in experiments where vision is prevented to situations where vision is permitted (see Pagano, Aten, & Alley, 1998) as well as the established view of visual dominance above the other modalities. Nevertheless, one can still assess the possible contributions of haptic perceived length in the present experiment.

3. One might think that posture is adapted to possible vibrations of the rod during the displacement of the cylinder. The center of percussion, or sweet spot, of an implement is the point of impact that produces the least vibration in the hand that holds the implement (cf. Carello, Thuot, Anderson, & Turvey, 1999). However, the center of percussion does not vary when mass of the rod is varied homogeneously. Therefore, any adaptations of behavior as a function of rod mass indicate the relative unimportance of the location of the sweet spot.

4. Note that the effect size of rod type is expected to be smaller than that of rod length because of the relatively larger range of manipulations of length than of mass.

5. We were concerned that randomizing versus blocking rod types within a session might affect the magnitude of the mass manipulation. Therefore, we repeated Experiment 2 on 8 participants, but with rod types grouped, such that participants reached with wooden rods on 1 day, aluminum rods on another day, and steel rods on yet another day. The results were all in the same direction as those reported earlier (Bongers, Smitsman, & Michaels, 1998).

6. To make certain that the range of lengths used caused the difference in results between Experiments 2 and 3, we reanalyzed the data of Experiment 2 for rods ranging in length from 0.4–0.8 m. The subset of Experiment 2's rods that approximated those used in Experiment 3 showed similar effects to the complete set from Experiment 2. The reaching distance was smaller for heavier rods, and the shoulder and elbow angles were adapted accordingly. Therefore, the difference between the two experiments—that heavy rods yielded larger reaching distances when the mass distribution was manipulated but a smaller reaching distance with homogeneous masses—was not an artifact of the range difference.

7. For Experiments 2 and 3, the effective length of the arm posture was analyzed with separate multivariate ANOVAs with rod length and rod type as the within-participant variables. We report here only the effects of rod type. Note that a larger effective length implies an extension of the arm. In Experiment 2, the arm was less extended for heavier rods (wood = 0.223 m, aluminum = 0.219 m, and steel = 0.206 m), $F(2, 20) = 15.85$, $p < .001$. That finding implies that the arm posture provided for less distance when heavier rods were used. Because a closer distance to the table was selected with heavier rods, the posture was anticipated in the distance. In Experiment 3, the arm was more extended for rods with weight at the tip, in particular, when only one weight was inserted (no weight = 0.223 m, one weight in handle = 0.221 m, one weight in tip = 0.226 m, two weights in handle = 0.224, and two weights in tip = 0.224 m), $F(4, 13) = 3.20$, $p = .05$. The chosen distance to the object was larger for rods with weight at the tip, which is in agreement with our finding that a larger distance to the object is selected with tip-weighted rods. In sum, postural adjustments were prospectively reflected in the distance.

8. There are "dynamic" models of reaching (Zaal, Bootsma, & Van Wieringen, 1999), but in those models abstract dynamic properties are emphasized and the use of tools is not explicitly addressed.

REFERENCES

Aruin, A. S., & Latash, M. L. (1995). Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. *Experimental Brain Research, 103,* 323–332.

Balasubramaniam, R., Riley, M. A., & Turvey, M. T. (2000). Specificity of postural sway to the demands of a precision task. *Gait and Posture, 11,* 12–24.

Bates, E., Carlson-Luden, V., & Bretherton, I. (1980). Perceptual aspects of tool using in infancy. *Infant Behavior and Development, 3,* 127–140.

Beak, S., Davids, K., & Bennett, S. (1999). Perception of affordances of haptic information in children and adults. In M. A. Grealy & J. A. Thompson (Eds.), *Studies in perception and action V* (pp. 215–218). London: Erlbaum.

Bongers, R. M., Smitsman, A. W., & Michaels, C. F. (1998). Perceiving reaching distance for a changed reaching system. In B. Bril, A. Ledebt, G. Dietrich, & A. Roby-Brami (Eds.), *Advances in perception-action coupling* (pp. 9–14). Paris: Editions EDK.

Bouisset, S., & Zattara, M. (1981). A sequence of postural movements precedes voluntary movements. *Neuroscience Letters, 22,* 263–270.

Bouisset, S., & Zattara, M. (1987). Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. *Journal of Biomechanics, 20,* 735–742.

Brown, J. E., & Frank, J. S. (1987). Influence of event anticipation on postural actions accompanying voluntary movement. *Experimental Brain Research, 67,* 645–650.

Bullock, D., Grossberg, S., & Guenther, F. H. (1993). A self-organizing neural model of motor equivalent reaching and tool use by a multijoint arm. *Journal of Cognitive Neuroscience, 5,* 408–435.

Carello, C., Fitzpatrick, P., Flascher, I., & Turvey, M. T. (1998). Inertial eigenvalues, rod density, and rod diameter in length perception by dynamic touch. *Perception & Psychophysics, 60,* 89–100.

Carello, C., Thuot, S., Anderson, K. L., & Turvey, M. T. (1999). Perceiving the sweet spot. *Perception, 28,* 307–320.

Chaffin, D. B., & Andersson, G. B. J. (1991). *Occupational biomechanics* (2nd ed.). New York: Wiley.

Ciriello, V. M., Snook, S. H., & Hughes, G. J. (1993). Further studies of psychophysically determined maximum acceptable weights and forces. *Human Factors, 35,* 175–186.

Crenna, P., Frigo, C., Massion, J., & Pedotti, A. (1987). Forward and backward axial synergies in man. *Experimental Brain Research, 65,* 538–548.

Cruse, H., Brüwer, M., & Dean, J. (1993). Control of three- and four-joint arm movement: Strategies for a manipulator with redundant degrees of freedom. *Journal of Motor Behavior, 25,* 131–139.

Cruse, H., Wischmeyer, E., Brüwer, M., Brockfeld, P., & Dress, A. (1990). On the cost functions for the control of the human arm movement. *Biological Cybernetics, 62,* 519–528.

Dean, J., & Brüwer, M. (1994). Control of human arm movements in two dimensions: Path and joint control in avoiding simple linear obstacles. *Experimental Brain Research, 97,* 497–514.

Dean, J., & Brüwer, M. (1997). Control of human arm movements in two dimensions: Influence of pointer length on obstacle avoidance. *Journal of Motor Behavior, 29,* 47–63.

Fitzpatrick, P., Carello, C., & Turvey, M. T. (1994). Eigenvalues of the inertia tensor and exteroception by the "muscular sense." *Neuroscience, 60,* 551–568.

Garg, A. (1989). An evaluation of the NIOSH guidelines for manual lifting, with special reference to horizontal distance. *American Industrial Hygiene Association Journal, 50,* 157–164.

Gibson, J. J. (1966). *The senses considered as perceptual systems.* Boston: Houghton Mifflin.

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Gibson, J. J. (1979). *The ecological approach to visual perception.* Boston: Houghton Mifflin.

Horak, F. B., Esselman, P., Anderson, M. E., & Lynch, M. K. (1984). The effects of movement velocity on associated postural adjustments made by normal and hemiplegic individuals. *Journal of Neurology, Neurosurgery, and Psychiatry, 47,* 1020–1028.

Kaminski, T. R., Bock, C., & Gentile, A. M. (1995). The coordination between trunk and arm motion during pointing movements. *Experimental Brain Research, 106,* 457–466.

Kingma, I., Beek, P. J., & Van Dieën, J. H. (2002). The inertia tensor versus static moment and mass in perceiving length and heaviness of hand-wielded rods. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 180–191.

Köhler, W. (1925). *The mentality of apes.* London: Kegan.

Konczak, J., Meeuwsen, H. J., & Cress, M. E. (1992). Changing affordances in stair climbing: The perception of maximum climbability in young and older adults. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 691–697.

Lacquaniti, F., & Soechting, J. F. (1982). Coordination of arm and wrist motion during a reaching task. *Journal of Neuroscience, 2,* 399–408.

Lee, W. A. (1980). Anticipatory control of postural and task muscles during rapid arm flexion. *Journal of Motor Behavior, 12,* 185–196.

Lee, W. A., Buchanan, T. S., & Rogers, M. W. (1987). Effects of arm acceleration and behavioral conditions on the organization of postural adjustments during arm flexion. *Experimental Brain Research, 66,* 257–270.

Lockman, J. J. (2000). A perception-action perspective on tool use development. *Child Development, 71,* 137–144.

Ma, S., & Feldman, A. G. (1995). Two functionally different synergies during arm reaching movements involving the trunk. *Journal of Neurophysiology, 73,* 2120–2122.

Massion, J. (1992). Movement, posture and equilibrium: Interaction and coordination. *Progress in Neurobiology, 38,* 35–56.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (1999). Problem solving in infancy: The emergence of an action plan. *Developmental Psychology, 35,* 1091–1101.

Norman, J. F., Todd, J. T., Perotti, V. J., & Tittle, J. S. (1996). The visual perception of three-dimensional length. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 173–186.

Oddsson, L. (1988). Co-ordination of a simple voluntary multi-joint movement with postural demands: Trunk extension in standing man. *Acta Physiologica Scandinavica, 134,* 109–118.

Oudejans, R. R. D., Michaels, C. F., Bakker, F. C., & Dolné, M. (1996). The relevance of action in perceiving affordances: Perception of catchableness of fly balls. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 879–891.

Pagano, C. C., Aten, T. R., & Alley, T. R. (1998, May). *Perceiving the lengths of rods wielded with and without vision.* Poster presented at the North American meeting of the International Society for Ecological Psychology, Trinity College, Hartford, CT.

Patton, J. L. Pai, Y.-C., & Lee, W. A. (1999). Evaluation of a model that determines the stability limits of dynamic balance. *Gait and Posture, 9,* 38–49.

Philbeck, J. W., & Loomis, J. M. (1997). Comparison of two indicators of perceived egocentric distance under full-cue and reduced-cue conditions. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 72–85.

Riccio, G. E., & Stoffregen, T. A. (1988). Affordances as constraints on the control of stance. *Human Movement Science, 7,* 265–300.

Riley, M. A., Mitra, S., Stoffregen, T. A., & Turvey, M. T. (1997). Influences of body lean and vision on unperturbed postural sway. *Motor Control, 1,* 229–246.

Rosenbaum, D. A., Loukopoulos, L. D., Meulenbroek, R. G. J., Vaughan, J., & Engelbrecht, S. E. (1995). Planning reaches by evaluating stored postures. *Psychological Review, 102,* 28–67.

Saling, M., Stelmach, G. E., Mescheriakov, S., & Berger, M. (1996). Prehension with trunk assisted reaching. *Behavioural Brain Research, 80,* 153–160.

Shaw, R. E., Flascher, O. M., & Kadar, E. E. (1995). Dimensionless invariants for intentional systems: Measuring the fit of vehicular activities to environmental layout. In J. M. Flach, P. A. Hancock, J. Caird, & K. J. Vicente (Eds.), *Global perspectives on the ecology of human-machine systems* (pp. 293–357). Hillsdale, NJ: Erlbaum.

Shaw, R. E., & Turvey, M. T. (1981). Coalitions as models of ecosystems: A realist perspective on perceptual organization. In M. Kubovy & J. Pomeranz (Eds.), *Perceptual organization* (pp. 343–415). Hillsdale, NJ: Erlbaum.

Smitsman, A. W. (1997). The development of tool use: Changing boundaries between organism and environment. In C. Dent-Read & P. Zukow-Goldring (Eds.), *Evolving explanations of development: Ecological approaches to organism-environment systems* (pp. 301–329). Washington, DC: American Psychological Association.

Smitsman, A. W., & Bongers, R. M. (in press). Tool use and tool making: A dynamical developmental perspective. In J. Valsiner & K. J. Connolly (Eds.), *Handbook of developmental psychology.* London: Sage.

Solomon, H. Y., & Turvey, M. T. (1988). Haptically perceiving the distances reachable with hand-held objects. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 404–427.

Steenbergen, B., Van der Kamp, J., Smitsman, A. W., & Carson, R. G. (1997). Spoon handling in two-to-four-year-old children. *Ecological Psychology, 9,* 113–129.

Turvey, M. T., & Carello, C. (1995). Dynamic touch. In W. Epstein, & S. Rogers (Eds.), *Handbook of perception and cognition: V. Perception of space and motion* (pp. 401–490). San Diego, CA: Academic Press.

Turvey, M. T., & Shaw, R. E. (1979). The primacy of perceiving: An ecological reformulation of perception for understanding memory. In L. G. Nilsson (Ed.), *Perspectives on memory research: Essays in honor of Uppsala University's 500th anniversary* (pp. 167–222). Hillsdale, NJ: Erlbaum.

Van der Fits, I. B. M., Klip, A. W. J., Van Eykeren, L. A., & Hadders-Algra, M. (1998). Postural adjustments accompanying fast pointing movements in standing, sitting and lying adults. *Experimental Brain Research, 120,* 202–216.

Van Leeuwen, L., Smitsman, A. W., & Van Leeuwen, C. (1994). Affordances, perceptual complexity and the development of tool use. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 174–191.

Wagman, J. B., & Carello, C. (2001). Affordances and inertial constraints on tool use. *Ecological Psychology, 13,* 173–195.

Wang, J., & Stelmach, G. E. (1998). Coordination among the body segments during reach-to-grasp action involving the trunk. *Experimental Brain Research, 123,* 346–350.

Warren, W. H., Jr. (1984). Perceiving affordances: Visual guidance of stair climbing. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 683–703.

Zaal, F. T. J. M., Bootsma, R. J., & Van Wieringen, P. C. W. (1999). Dynamics of reaching for stationary and moving objects: Data and model. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 149–161.

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